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Quartermaster Research & Engineering Center, US Army

Natick, Massachusetts

TEXTILE, CLOTHING AND FOOTWEAR DIVISION

Clothing Branch Report No. 9

EVAPORATIVE COOLING IN SPACER SYSTEMS

by

Lyman Fourt

HARRIS RESEARCH LABORATORIES, INC.

Project Reference
7-79-10-001A

July 1958

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FOREWORD

This is the third report under a contract covering investigation of the principles of spacers suitable for use in hot weather clothing.

This report was prepared by Harris Research Laboratories under contract No. DA 19-129-QM-1040, Headquarters Quartermaster Research and Engineering Command, Quartermaster Research and Engineering Center, US Army. The contract was initiated under Project No. 7-79-10-001-A and was administered under the direction of the Textile, Clothing and Footwear Division, Headquarters Quartermaster Research and Engineering Center, with Mr. Theodore L. Bailey and Mr. C. J. Monego acting as project leaders.

This material is taken from contract Report No. 3 for the quarter ending 14 July 1958.

The results of the experimental work described in this report are directly applicable in the design of the multipurpose, combined protection ensemble for which requirements have recently been put forth. Such a combined protection ensemble must provide some degree of protection against all of the hazards of the modern combat battlefield. In order to do so, without imposing excessive heat stress in hot climate areas of operation in the course of global warfare, a simple means of ventilation must be provided to the wearer. The current approach is to use a protective shell so designed as to allow a space between the shell and the wearer which will permit ventilation with its accompanying convective and evaporative cooling.

This report describes the advances made by the Harris Research Laboratories in this study. The establishing of the dimensions of the spacing which permits a maximum degree of heat dissipation and can still be designed into a practical battlefield uniform is an important step. The concept of designing a uniform on the spacer principle had initially proceeded on the basis of theoretical considerations only. In addition, the report describes and quantitates some of the other factors involved in the design considerations of the spacer uniform.

SPACER SYSTEMS FOR HOT WEATHER CLOTHING

Contract No. DA-19-129-QM-1040
Project No. 7-79-10-001 A
O.I. 6018

HARRIS RESEARCH LABORATORIES, INC.
1246 Taylor Street, N.W.
Washington 11, D. C.

Quarterly Report No. 3

Period ending July 14, 1958

EVAPORATIVE COOLING IN SPACER SYSTEMS

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EVAPORATIVE COOLING IN SPACER SYSTEMS

SUMMARY

1. The results indicate that in practical design of garments for maximum cooling by means of spacers:

a. The channels should not be much less than one inch in smallest dimension, but gain little by being larger than 2 inches.

b. Several shorter channels with the entrances of higher channels independent of the exits of lower ones will be more effective than one long channel.

2. The evaporative heat loss from a vertical column approximating the scale of an arm or a leg has been measured under conditions of air movement limited to natural convection. At distances of 6 inches or more from skin to spacer wall, the evaporative cooling under natural convection conditions is proportional to the vapor pressure difference between the skin and the general environment.

3. Evaporative loss resembles dry heat loss in that the lower third of the column, which first encounters the fresh air, loses more heat by evaporation than the second (middle) or third (upper) segment. The evaporative loss from the last third of the column is less than from the middle, even without any spacer.

4. The restrictive effect of a spacer parallel to and everywhere equally separated from the evaporative surface increases with narrowing separation. With either 2 or 1 inches separation, there is an upper limit on the amount of cooling, so that the full capacity for evaporative cooling cannot be realized, above a certain vapor pressure difference. For each size spacer, there is a range of high humidities over which the humidity is the limiting factor*, and a range of lower environmental humidities, in which the spacer is the limiting factor.

5. In dry to moderate humidities, the amount of evaporative cooling possible with 1 or 2 inch spacers, completely unobstructed, is substantial, permitting heat balance to be maintained under "moderate work", about 200 kg cal/m^2 hr, if the present results can be extended to the whole body. However, the trend lines show that the cooling would fall off rapidly in going below 1 inch for the spacer. Obstruction effects will also reduce the cooling in real systems, and as the environmental temperature rises, there will be additional loss of cooling, both in direct loss

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* At high humidities, narrower spacers set limits farther below the environmental limit, while spacers with more clearance will permit closer approach to the environmental limit.

of sensible heat, and through interaction, by way of specific gravity effects, on the air movement needed for cooling.

On the favorable side, bodily motion, although increasing heat production, will also increase air motion and thus promote evaporative cooling above the levels measured here for natural convection conditions.

DETAILS

Scope of this report:

This report deals exclusively with evaporative cooling, which has been measured directly by weighing. There is also loss of sensible heat from the test system to the environment, but this is much smaller, some 40 kg/cal m^2 hr. or less, and is mainly independent. The two types of loss are interconnected through their effects on rate of air movement by natural convection or chimney effect. This interconnection is a second order effect, which, however, becomes more important as the environmental temperature approaches and goes above skin temperature. The present tests involved environments near 80 - 85°F and skin temperatures near 94°F, conditions in which evaporative (latent heat) and direct (sensible heat) cooling are largely independent. The results apply to all lower environmental temperatures, but further information is needed for temperatures above 90°F.

Notes on method:

The scale of these tests is that of the arm or lower leg, with a cylinder 3 inches in diameter, 21 inches high, composed of separable, interchangeable segments each 7 inches high. The surface temperature of the segments varies between 33.5 and 34.5°C with the on-off cycle of the temperature controls, giving an average saturation vapor pressure of water vapor close to 40 mm Hg. The surface water content varies from 500 to 200 g/m^2 during the tests, and water content is determined by weighing to ± 0.01 gram, which is approximately 0.2 g/m^2. The individual segments are weighed in addition to the system as a whole.

The cylinder system is sheltered in a chamber 27 inches high, 18 inches wide and 20 inches deep. The nearest approach of the cylinder surface to a wall is 6 inches from the center of the 20 inch side.

The period of an individual test is 30 minutes, during which time only about half the water originally added is evaporated, in the most rapidly drying segment, assuring that the surface is saturated throughout the test.

The "spacers" used in these tests were cylinders of transparent cellulose acetate sheeting, the same length as the test cylinders, arranged concentrically and at the same level. These spacers, 0.005 inches thick, are low in thermal insulation, and are windproof and essentially water vapor impermeable in the present circumstances.

Effect of spacers on whole system:

The effect of spacers with 6 inches or more separation (essentially no spacer), is shown in Figure 1. The line in this chart indicates the evaporative cooling for very large spacers (or none at all), as determined from the highest rates of evaporation observed with no wall closer to the sides of the cylinder than 6 inches. This line is extended to the origin at zero vapor pressure difference and zero evaporative cooling, since it must start at this point.

Observations are also shown for 2 inch, 1 inch, and half inch spacers, at a range of vapor pressure differences obtained by operating on different days, and by extending the range of natural conditions by using a dehumidifier in the test room.

The results show that there is a limit of evaporative cooling with a given spacer, this limit being lower, the narrower the distance to the wall. There is a small upward slope of the rate of evaporation with increased vapor pressure difference, even though the spacer is present, but the practical interpretation is that each size spacer sets an upper limit, or shuts off most of the potential for increased evaporation in drier atmospheres.

This is to be expected, of course, since the rising column of air between spacer and saturated surface tends to become more saturated as it rises, decreasing the local potential for further evaporation.

Comparison of separate segments:

Figure 2 shows the rate of evaporative cooling, averaged for vapor pressure differences between 20 and 30 mm, in relation to distance from skin to wall. This is shown for the present 3 x 21 inch system as a whole, and for each 7 inch segment separately. For convenience, the results in the chamber itself are plotted at 6 inches, but the slope has levelled off so much that this condition is representative of wider spacers or no spacer at all.

The rate of change is greater at the smaller spaces, and must increase even more rapidly, for still smaller spaces.

In all conditions, the evaporation from the first section which the fresh air encounters is greatest, and from the last (here the third) segment, the least. However, as space allowance is narrowed, the rate lowers for each.

Bearing on practical clothing design:

The results have several implications for design of garments:

1. The limit effect indicates that the design of clothing should be directed to numerous short vertical channels, rather than toward longer ones with fewer entrances and exits.

2. Design in which the upper entrances are stepped sideways from the exits of lower channels would be of some advantage, to secure that entering air had less likelihood of having been partially saturated from passage through lower channels.

3. The upper limit for evaporative cooling under natural convection conditions, for channels on the present scale, is about 220 Kg cal/m^2 hr for 2 inch channels, and about 180 Kg cal/m^2 hr, for 1 inch channels. The limit must drop much more rapidly for smaller channels. These limits, however, permit considerable evaporative cooling, if sufficient vapor pressure difference is available, that is, if the environment is not too humid. This general level of 180 - 220 Kg cal/m^2 corresponds to light to moderate work (Ref. 1).

Caution is necessary in viewing these results as promising for comfort in hot environments, however, since these are obtained for "pure spacer" conditions, with the minimum degree of obstruction. Real clothing systems embodying spacers would have considerable obstruction to air flow resulting from garment design, closures to keep off rain or toxic agents, space maintaining elements, and heavy load bearing elements, even if load bearing types of spacer elements were used to support packs, shoulder straps, belts, and bullet or fragment resisting elements.

<u>Environmental limits:</u>

To the extent that the interaction of temperature differences and vapor pressure differences can be neglected, it is possible from the data available to

outline the relation of the present results to ranges of temperature below 90°F, and to the relative humidity of the environment. The present outline is a first approximation or prospectus and should be used with increasing caution, the nearer the environmental temperature is to the skin temperature. It is expected to prove to be a better approximation from 90°F downwards in temperature, than above 90°F. Since it is a forecast or preliminary sketch, the chart in Figue 3 is given only on a large interval scale. Further calibration will be required before the relations of the environment to maximum potential cooling in spacer systems can be pin-pointed.

Figure 3 reproduces the data for larger spacers, in outline form. It also gives scales of relative humidity, at a series of dry bulb temperatures. A wholly wet skin at close to 94°F surface temperature, corresponding to a saturation pressure of water vapor of 40 mm Hg, and minimum air movement, limited to natural convection, are assumed. Air movement or body movement will increase the cooling. This chart can be used to approximate the environment limits within which the environment itself is the limit (indicated to the left of the dashed lines), and to locate the drier environments (to the right of the dashed lines), within which the spacer sets the limit*.

It should be noted that this chart is based on and is best for environments which are below skin temperature. In these cooler environments, the effect of direct or "sensible" heat loss increases by approximately 50 Kg cal/m^2 hr for each 12.5°F, or 7.2 Kg cal/m^2 hr. per 1°C (Ref. 2). This is within the range (8.3 to 5.0) for the rates of loss of sensible heat from dry

* For narrow spacers, such as 1/2 inch, the limit at high humidities falls far below that of the environment.

7 inch segments, as given in Table 2 of Report 2. The need for evaporative cooling, of course, drops off at lower air temperatures as the direct or sensible cooling increases, and increases for air temperatures above skin temperature.

Additional data are needed, however, before such a chart can be very safely extended to higher temperatures, where guidance is more needed. The reason for caution is that air movement by natural convection depends upon density difference, and the density of an air-water vapor mixture depends both on its temperature and on its water content. In general, environmental air originally above skin temperature will be cooled by the evaporation taking place at the skin, and tend to become more dense for this reason, although simultaneously tending to become less dense because water vapor (molecular weight 18) is less dense than air (average molecular wt. 29). Figure 4 shows the density-temperature-moisture relations at normal barometric pressure (760 mm) (Ref. 3) and divides, by a dashed line at the density of saturated air at 95°F, the region below which air will rise in a channel between spacer and skin, and above which air will descend. In the region surrounding this line, however, there may be a considerable range of stagnant conditions where some other means of securing air movement, in addition to density differences, could be most welcome.

It is because this expected region of difficulty lies close above the conditions of the present tests that one cannot extend the chart to higher temperatures, with as much confidence as would be wished, until more data is available.

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1. Newburgh, L. H., Physiology of Heat Regulation, p. 446. Saunders, Philadelphia, 1949.

2. Belding, H. S., in Newburg, L. H. (ibid.) p. 353

3a. Am. Soc. Heating & Ventilating Engineers, Heating, Ventilating, and Air Conditioning Guide, 1944, Table 6, Page 10.

3b. "Density of Moist Air", tables in Handbook of Chemistry and Physics, C. D. Hodgman, Ed. (27th Ed, p. 1620 ff) Chemical Rubber Publishing Co., Cleveland (1943).

Figure 1, Report 3 (QM 1040)

Limits on evaporative cooling set by spacers 2" or 1" from skin. The dashed line shows the environmental limit set by atmospheric humidity, as determined from maximum evaporation rates with no spacer (open circles). With a spacer, however, an upper limit is reached, so that the full potential for evaporation in drier atmospheres is not realized.

Note added August 8, 1958:

Data for half inch spacers have been added, which show more severe limitation at higher humidities than had been found for 2 and 1 inch spacers. Footnotes in the text modify the discussion to include the results on half inch spacers.

Fig. 1, Report 3 (QM 1040)

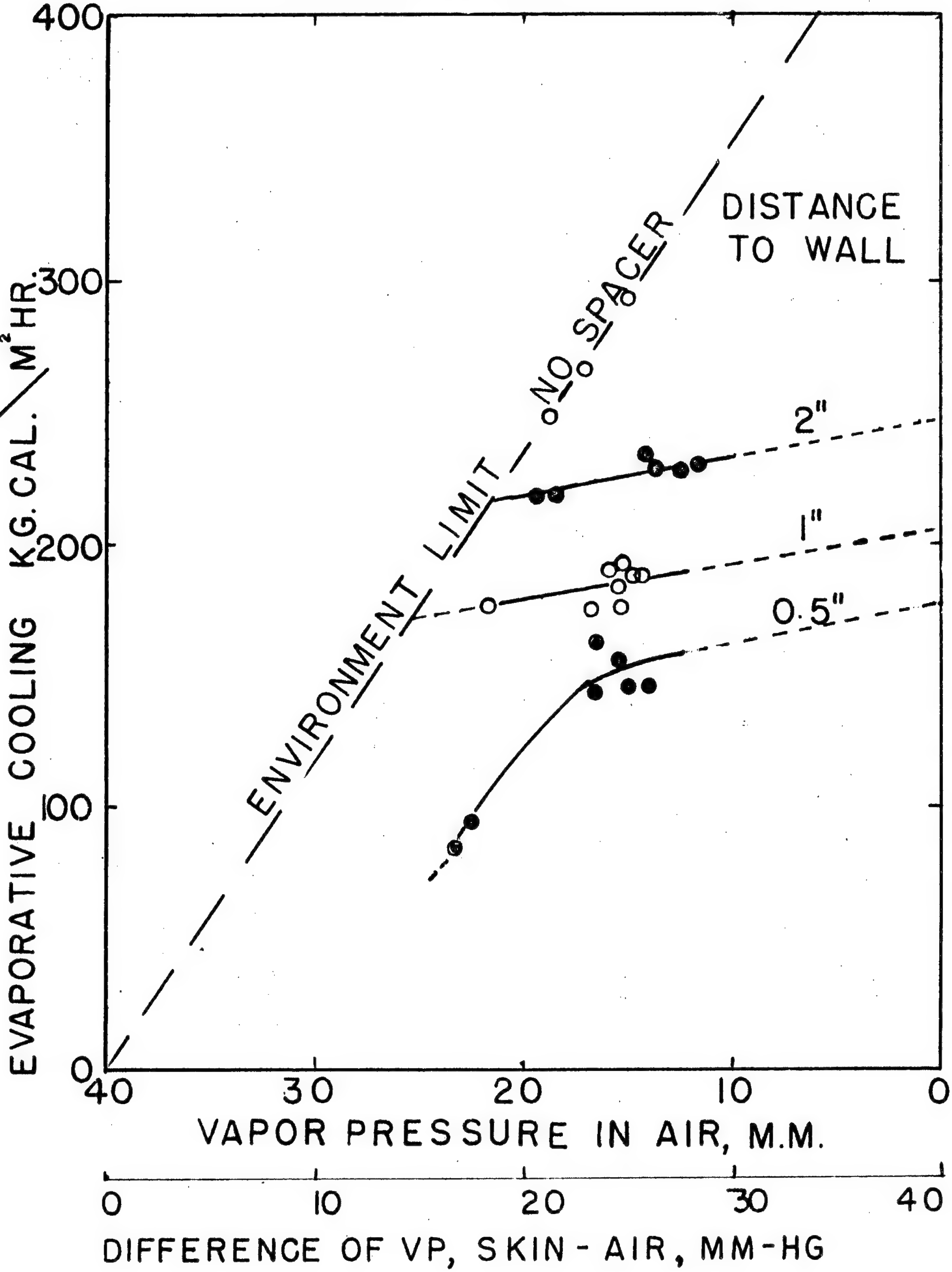

Figure 2, Report 3 (QM 1040)

Effect of distance between evaporating surface and spacer wall, on evaporative cooling, with 20 to 30 mm vapor pressure difference (moderate to dry environment). Test cylinder is 3" in diameter, with 3 segments, each 7" high. Tests are all with the 3 segments arranged one above another, at an average skin temperature near 34°C. The rates are given per unit area for the individual segments as well as for the combination. The combined result is the total water loss from all three divided by the total evaporating area.

Results for half inch separation are limited to the range near 15 mm vapor pressure, 25 mm vapor pressure difference.

In more humid environments, all rates of evaporative cooling will be lower, the more so the narrower the spacer separation.

Fig. 2, Report 3 (Qm 1040)

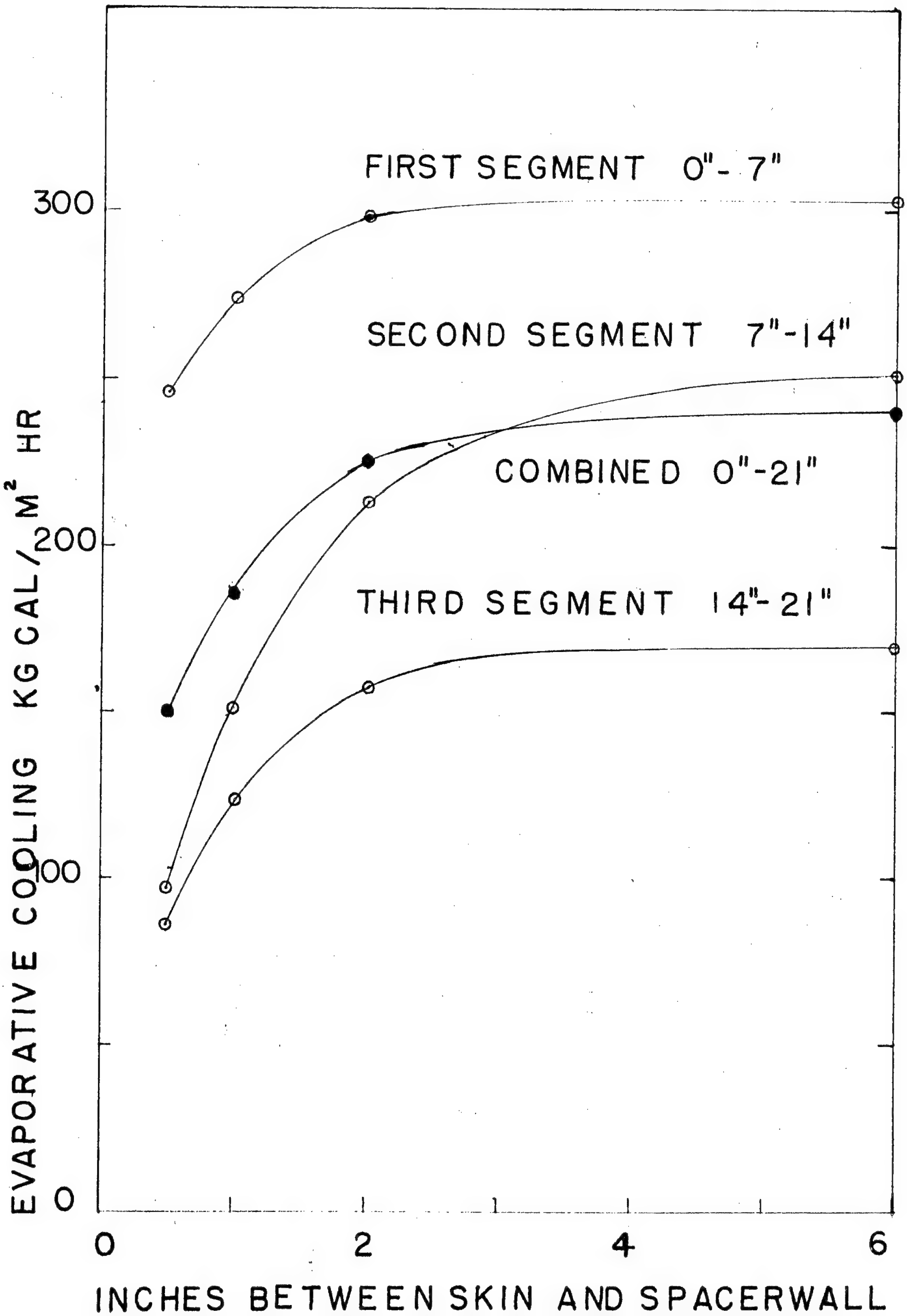

Figure 3, Report 4 (QM 1040)

Limits of evaporative cooling in terms of environment and spacer, for spacers with 1 inch or greater separation.

The lower part of the chart shows temperature versus vapor pressure, for relative humidity as indicated by the curved lines. In environments to the left of the broken lines, the humidity limits the evaporative cooling. To the right of the broken lines, the spacer sets the limit for evaporative cooling.

This chart is for minimum air movement, in which air movement is limited to natural convection. These are the most severe environmental conditions possible, from the point of view of evaporative cooling, approximately those of a closed telephone booth with no fan. However, clothing without spacers but with substantial thermal insulation will usually increase the heat burden and decrease the cooling, in comparison with spacers. On the other hand, air movement by wind, or by forced ventilation, or by bodily movement, will increase evaporative cooling.

This chart is a preliminary outline, to serve as a prospectus for more complete information. Caution is advised in its use for air temperatures near skin temperatures, since air movement by natural convection may be more difficult, especially between 90°F and 100°F.

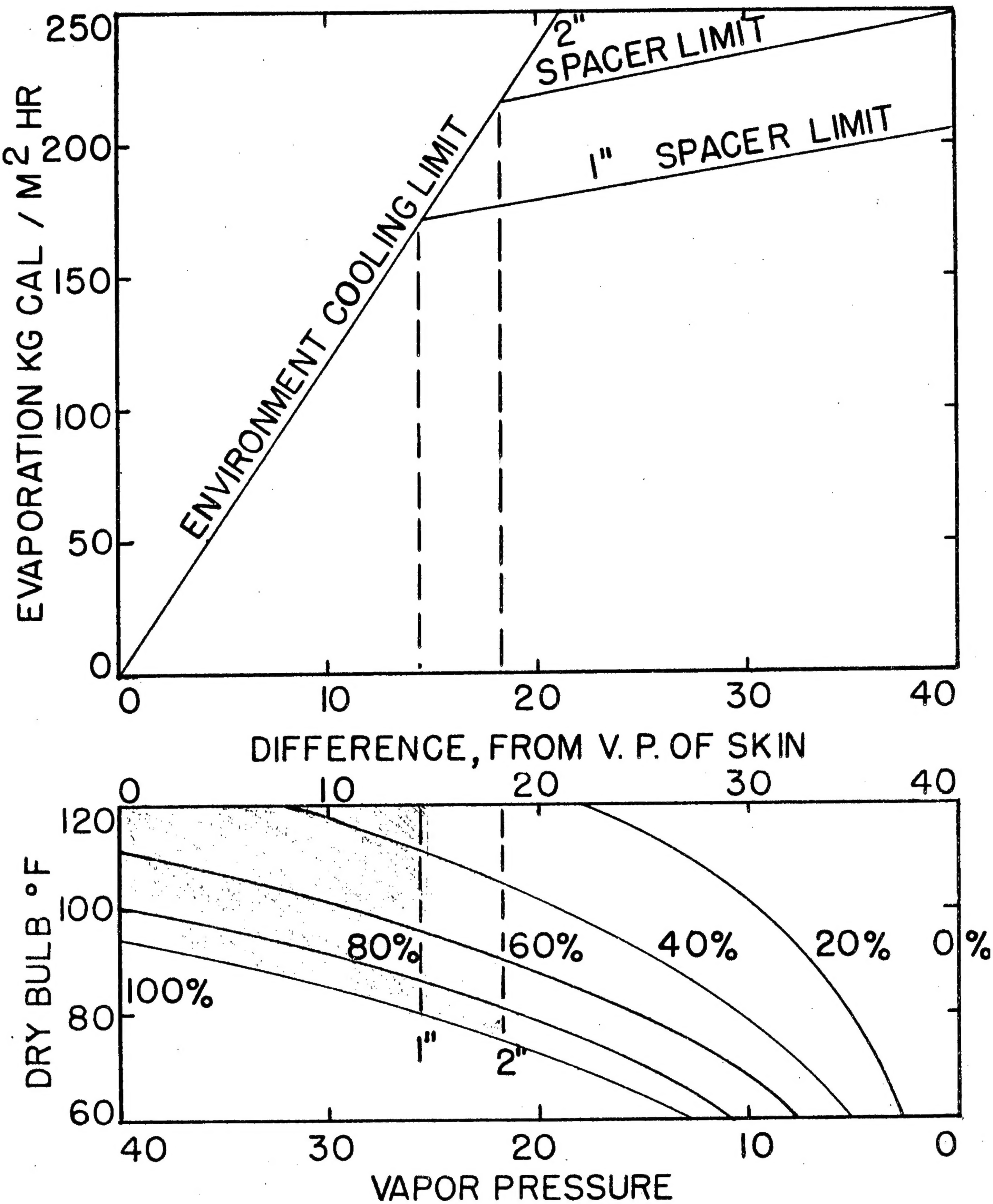

Fig . 3, Report 4 (QM 1040).

Figure 4, Report 3 (QM 1040)

Density of moist air at 760 mm barometric pressure.

The density is shown on the vertical axis, with light air at the top and heavier air below. The relative humidity is shown on the horizontal axis, and the temperature at which moist air has a given density is given along slanting straight lines, marked in both °C and °F. A dashed line indicates the density of saturated air at 35°C (95°F), a high but possible skin temperature. Cooler air will rise as it becomes saturated and warmed to skin temperature.

Warmer air which is not too moist can be cooled by evaporation at the skin, and may become more dense if the cooling effect exceeds that of adding water vapor, so that it may flow downward next to the skin, like the current of air down a pitcher of ice water.

Warm moist air in which the vapor pressure is above that of saturation at skin temperature (taken as 35°C, 95°F here) cannot be cooled to that temperature by evaporation. Instead, the skin will receive heat from condensation from such air, and will tend to rise toward the wet bulb temperature of the air. The saturation limit, above which the vapor pressure exceeds that of the skin, is indicated by the line SL, which intersects the temperature lines at the relative humidity values corresponding to the saturation vapor pressure at the skin temperature. Fortunately, conditions above the saturation limit are seldom encountered.

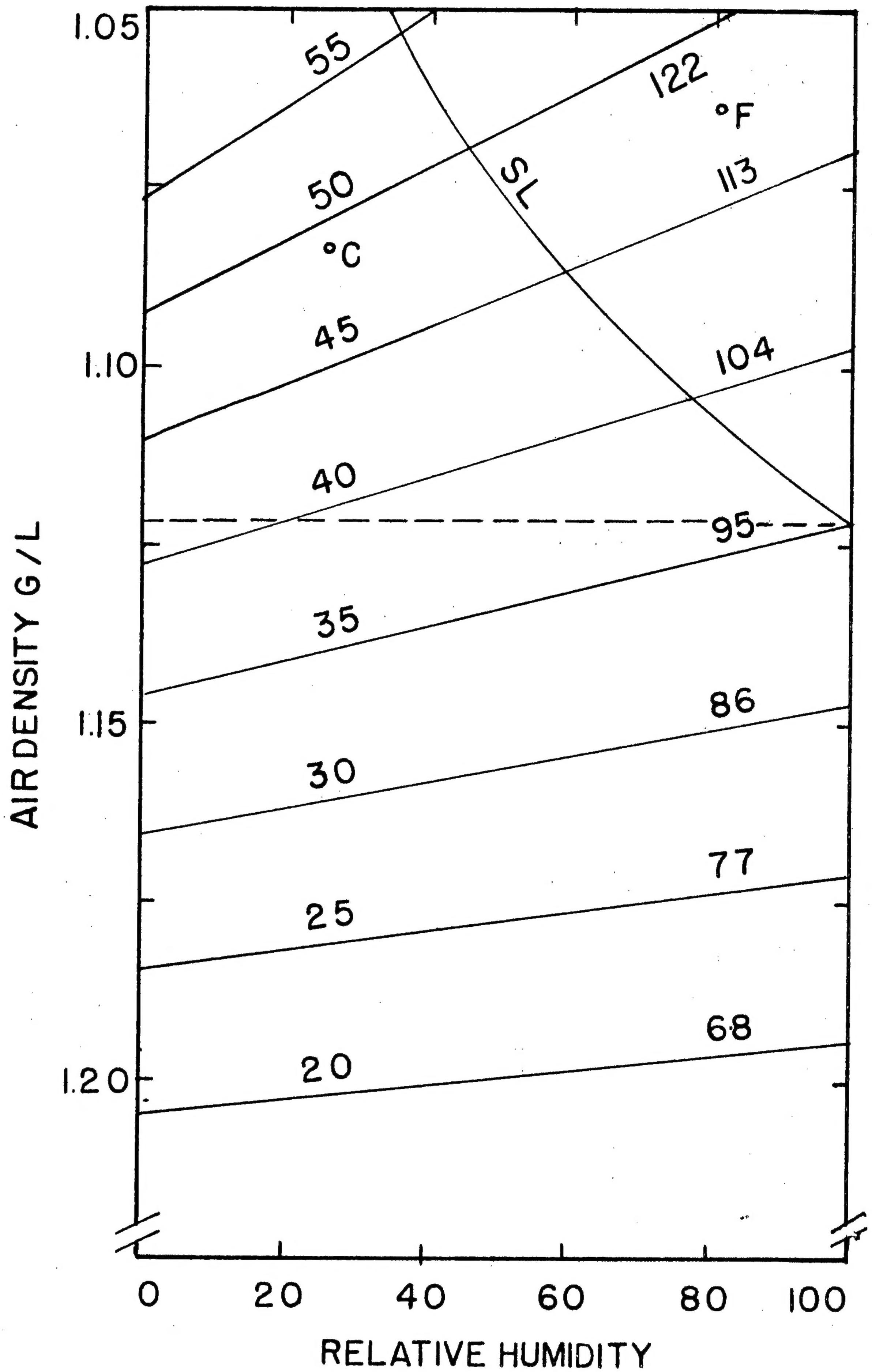

Fig. 4, Report 3 (QM 1040).